Wind/EPACT Observations of Temporal Evolution in Elemental Composition during Large Solar Energetic Particle Events

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Abstract

With a collecting power of 51 cm^2-sr, the Low-Energy Matrix Telescope (LEMT) in the *Wind* satellite's Energetic Particle Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995; Reames et al. 1997) provides unprecedented high-precision studies of the temporal evolution in elemental abundances during solar energetic particle (SEP) events at ~2-10 MeV/nuc. We briefly review recently published studies of the 20 April 1998 SEP event (Tylka, Reames, & Ng 1999), which showed dramatic systematic compositional variation that can be largely understood in terms of transport through a time-dependent Alfvén wavefield generated by the streaming energetic protons (Ng, Reames, & Tylka 1999). We compare those results to the 24 April 1999 SEP event, which was caused by a similar fast, western coronal mass ejection (CME) but had a much softer proton spectrum, thereby leading to much weaker compositional variation. We also briefly comment on other events with different patterns of compositional evolution, which may also be significantly influenced by proton-generated waves.

1 The 20 April 1998 Solar Energetic Particle Event

In terms of total proton fluence above 10 MeV, the 20 April 1998 SEP event is the largest seen thus far in Solar Cycle 23. This event was caused by a large CME detected by *SoHO*/LASCO near the western limb at a speed of ~1600 km/s. *GOES* observed an M1.4 x-ray flare, and although no Hα flare has been reported for this event, the peak x-ray intensity observed on *Yohkoh* during this event was at S23W87 (J. Mariska, private communication). Figure 1 shows hourly-averaged intensities from *Wind*/EPACT. The highest intensities in the ~2 MeV proton channel are near the streaming limit of several hundred protons/cm^2-s-sr-MeV identified by Ng and Reames (1994). The far-eastern flank of the CME-driven shock arrived at *Wind* late on 23 April, corresponding to mean transit speed of ~520 km/s. Upon arrival at *Wind*, the shock was too slow to accelerate particles, and no "shock spike" increases were observed in EPACT intensities.

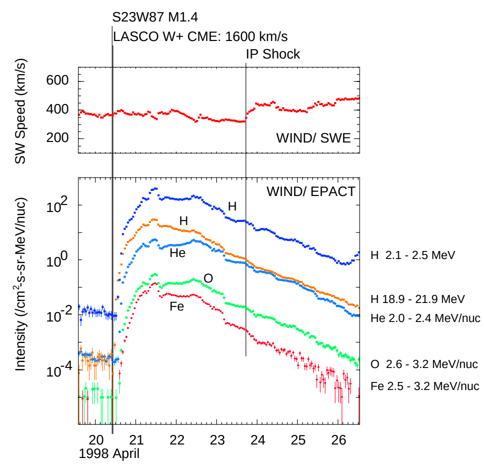

Figure 1: *Wind* hourly-averaged solar wind speed (top) and particle intensities (bottom) during the 20 April 1998 event. *Wind* was at ~220 R_E sunward of Earth during this event.

Figure 2 shows hourly-averaged elemental abundance ratios in three energy intervals from LEMT. All ratios have been normalized to reference values given by Reames (1995). The evolution of Fe/O is particularly striking. Fe/O drops rapidly from an initially enhanced value during the first few hours of the event. Such onset behavior has been observed before (Mason, Gloeckler, & Hovestadt 1983) and is consistent with mass-to-charge (A/Q) dependent transport through a background wave spectrum early in the event. Fe/O then rebounds and continues to rise

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14. ABSTRACT

With a collecting power of 51 cm2-sr, the Low-Energy Matrix Telescope (LEMT) in the Wind satellite?s Energetic Particle Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995; Reames et al. 1997) provides unprecedented high-precision studies of the temporal evolution in elemental abundances during solar energetic particle (SEP) events at ~2-10 MeV/nuc. We briefly review recently published studies of the 20 April 1998 SEP event (Tylka, Reames, & Ng 1999), which showed dramatic systematic compositional variation that can be largely understood in terms of transport through a time-dependent Alfv?n wavefield generated by the streaming energetic protons (Ng, Reames, & Tylka 1999). We compare those results to the 24 April 1999 SEP event, which was caused by a similar fast western coronal mass ejection (CME) but had a much softer proton spectrum, thereby leading to much weaker compositional variation. We also briefly comment on other events with different patterns of compositional evolution, which may also be significantly influenced by proton-generated waves.

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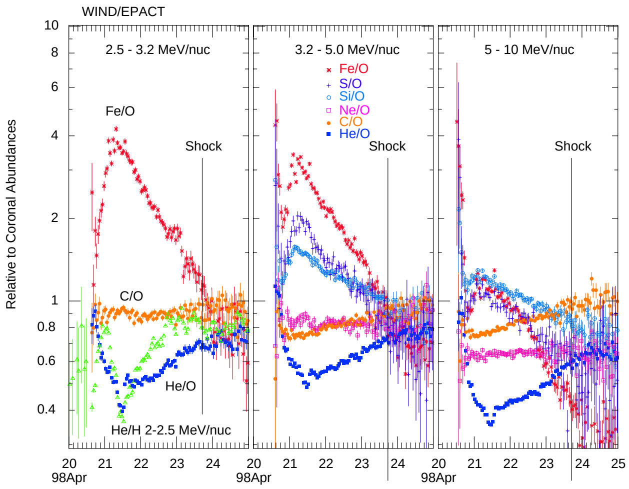

Figure 2: Hourly-averaged abundance ratios (normalized to coronal values [Reames 1995]) from *Wind*/EPACT during the 20 April 1998 event. See Tylka, Reames, & Ng (1999) for additional details. In the middle panel, elements appear in the same order from top to bottom as in the legend. The same symbols are used in the other panels.

over the next 12 hours, until the time of peak intensity. Thereafter, Fe/O declines exponentially over the next two days until shock passage, at which time Fe/O flattens out. This behavior is mirrored by He/O which declines (increases) while Fe/O rises (falls). The middle panel includes additional elements at slightly higher energies, which demonstrate behavior that is well-organized by the ions' A/Q ratios. At even higher energies (third panel), Fe/O is near its coronal value at the peak of the event but is smaller later. Fe/O is strongly suppressed at higher *ACE*/SIS energies (von Rosenvinge et al. 1999). The clear A/Q ordering seen in the middle panel also breaks down in the third panel, with Si/O (and even He/O and C/O late in the event) above Fe/O. These re-ordering effects are much too large to be explained by time- or energy-dependence in the ionic charge states.

The He/H ratio at ~2 MeV/nuc in the left panel of Figure 2 is especially noteworthy. For most of the event, the evolution in this ratio is opposite to that of Fe/O. Because of the Fe charge state (~10-14), the numerator has ~twice the rigidity of the denominator in both Fe/O and He/H. Different temporal behavior in these two ratios would therefore not be expected if *only* scattering from a background Kolmogorov wave spectrum, with λ as a simple increasing power-law in rigidity, were involved. The difference between Fe/O and He/H suggests that a dynamic wave spectrum, generated by the streaming energetic particles themselves, plays a fundamental role in this event. This explanation is further bolstered by: (1) the observed particle spectra, which show flattening at low rigidities which may be imputed to rigidity-dependent escape from the shock region (see Tylka Reames, & Ng 1999); and (2) numerical simulations (Ng et al. 1999) which qualitatively reproduce key features of this event, including the Fe/O and He/H variations in Figure 2. These simulations explicitly include time-dependent proton-generated waves from a shock that begins strong but weakens continuously.

Abundance variations in the 20 April 1998 event may thus be understood as preferential escape of high A/Q species from a *distant* shock-accelerator. One might therefore expect to see depletions of high A/Q species *near* a powerful shock. Such behavior is indeed observed in the "energetic storm particle" (ESP) event of 26 August 1998 (Tylka, Reames, & Ng 1999; Reames 1999), which produced the highest intensities of ~MeV particles observed so far at Earth in Solar Cycle 23.

2 The 24 April 1999 Solar Energetic Particle Event

The 24 April 1999 event (Figures 3 and 4) offers instructive comparisons with the 20 April 1998 event. This event was also produced by a fast western CME, with a preliminary speed estimate of ~1400 km/s [http://lasco-www.nrl.navy.mil/cmelist.html]. However, in this case, there was neither flare nor a *SoHO*/EIT disturbance on the visible solar disk [B. Thompson, private communication], and the CME launched from the *backside* of the Sun. Based on the CME's ~N20 heliolatitude, NOAA suggested that this event was associated with AR 8517, which had rotated out of view 2.5 days earlier. This association

would put the source at ~W125. Correcting for projection effects would thus make the actual leading-edge CME speed roughly the same as the ~1600 km/s of the 20 April 1998 event. Pre-event particle intensities and the observed solar-wind speeds during the main phases of the events were also quite comparable. Thus, both the causative CMEs and near-Earth interplanetary conditions were similar for the two events.

Maximum 2 MeV-proton intensity in this event was also near the streaming limit (Ng & Reames 1994), although the plateau intensity persisted for a much briefer period than in the 20 April 1998 event. All other particle intensities were much smaller than in the 20 April 1998 event. In particular, Figures 1 and 3 show that the 20 MeV proton intensity was smaller by ~two orders of magnitude. The proton spectrum in this event was thus much softer, consistent with connection to weaker parts of a CME-driven shock front.

Given the soft proton spectrum, this event presumably lacked the streaming high-energy protons which generated the waves responsible for the dramatic modulation of heavy-ion abundances in the 20 April 1998 event. As shown in Figure 4, this indeed appears to be the case. The event shows the same onset behavior in the first ~6 hours as in the 20 April 1998 event, with Fe/O dropping rapidly from initially enhanced levels while He/H rises. Thus, early in the event there were sufficient proton-generated waves to affect He/H at low energies. However, because of the steep proton spectrum, there were insufficient proton-generated waves to strongly affect higher-rigidity particles, and the dramatic subsequent Fe/O enhancements of the 20 April 1998 event were not seen here. Instead, both Fe/O and He/H are roughly constant for ~18 hours, at levels somewhat below nominal coronal values. There is a hint of Fe/O returning to the coronal value later, but that cannot be unambiguously established due to poor data recovery.

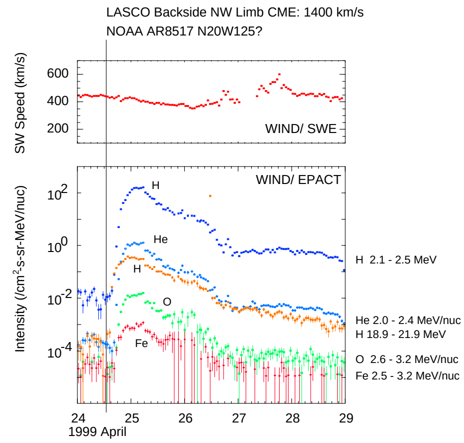

Figure 3: *Wind* hourly-averaged solar wind speed (top) and particle intensities (bottom) during the 24 April 1999 event. Large error bars in the middle of the event are due to intermittent data recovery. *Wind* was beyond 30 R_E throughout this event.

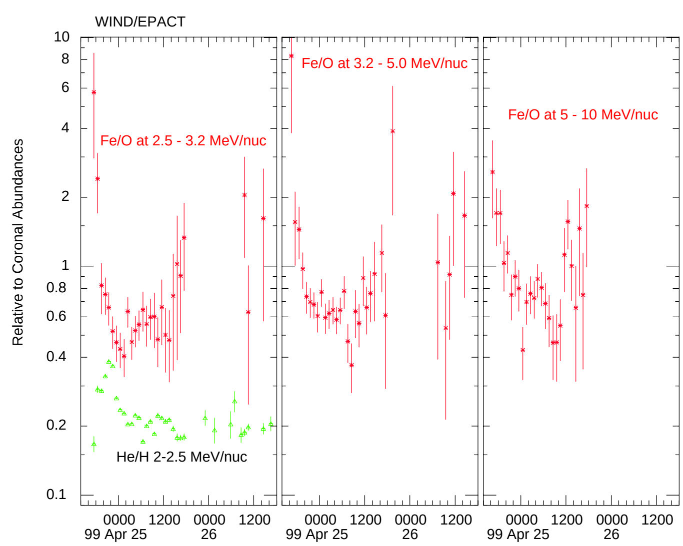

Figure 4: Fe/O and (in the left panel) He/H during the 24 April 1999 event, normalized to Reames (1995) coronal values. Poor data recovery from *Wind* causes the datagaps and large error bars late in the event.

3 The 6 November 1997 and 14 November 1998 Events

Figures 5 and 6 show hourly abundance ratios in two other large events, 6 November 1997 and 14 November 1998, respectively. After changes in the first ~12 hours of the events, abundance ratios other than He/O are relatively constant. Fe/O is persistently enhanced in these events. In addition, Fe/O clearly

rises with increasing energy in this energy range in the 1997 event. Both of these events are well-connected western events with relatively hard proton spectra. In these cases, the shock weakens more slowly than in the 20 April 1998 event, and high intensities of proton-generated waves may distort the composition for a longer period of time. Detailed simulations, to investigate to what extent proton-generated waves may account for the observed behavior, have not yet been completed. Modeling these two events may be further complicated by the particles, waves, and interplanetary structures produced by large, preceding CME-driven events on 4 November 1997 and 6 November 1998, respectively.

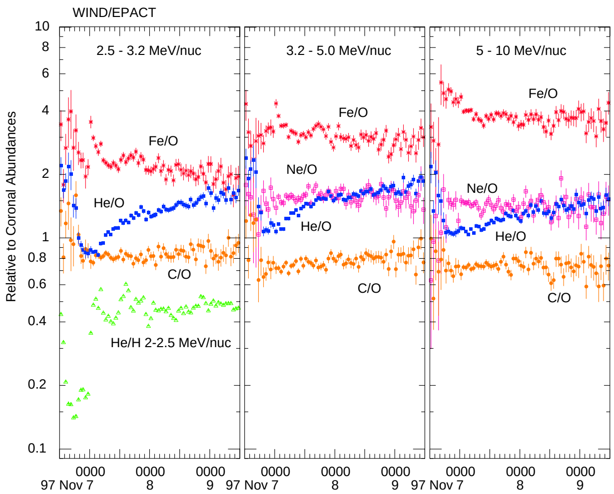

Figure 5: Hourly abundance ratios, normalized to Reames (1995), in the 6 November 1997 event.

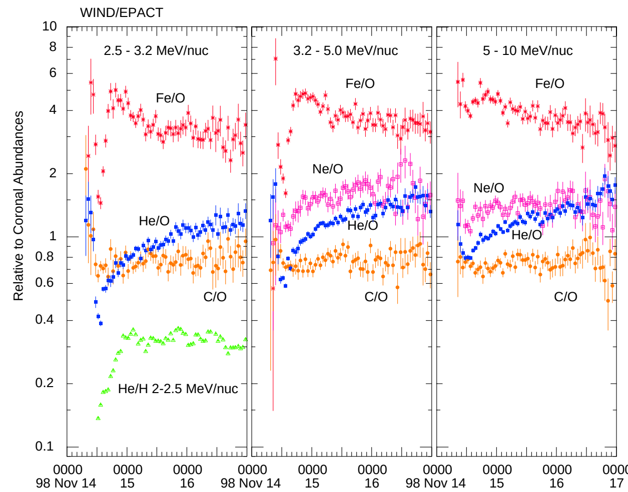

Figure 6: Hourly abundance ratios, normalized to Reames (1995), in the 14 November 1998 event.

4 Discussion

Wind/EPACT has revealed complex patterns in the temporal evolution of elemental abundances in gradual solar particle events. The most dramatic of these events (20 April 1998) suggests that careful treatment of Alfvén waves generated by streaming protons (Lee 1983; 1997) may hold the key to understanding these new observations. Qualitative features of other events (e.g., 26 August 1998 and 24 April 1999) are also consistent with this interpretation. Although it is not clear that all of the observations presented here can be explained by such effects, the potential impact of proton-generated waves should be considered while exploring alternative interpretations of SEP compositional anomalies and variability.

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